The Population Consequences of Disturbance Model Application to North Atlantic Right Whales (*Eubalaena Glacialis*)

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LONG-TERM GOALS

Anthropogenic noise is known to cause both behavioral and physiological changes in marine mammals, but the potential for long-term population effects is not known. The Population Consequences of Acoustic Disurbance (PCAD) model (NRC 2005) provided a framework to trace the effects of acoustic disturbance through the life history of a marine mammal to its population status. Developments in the model have been designed to determine if the effects of *any* disturbance can be traced from individuals to the population by way of changes in either behavior or physiology (see Figure 1), and the revised approach is called PCOD (Population Consequences Of Disturbance) . In North Atlantic right whales (*Eubalaena glacialis*), extensive data on health and body condition, anthropogenic impacts, and individual life history exists. The primary goal of this study is to model visual observations of health, human impacts (including entanglements and ship strikes), and whale locations to provide estimates of true underlying condition and individual level survival for right whales. Secondary goals include modeling fecundity, and exploring the feasibility of incorporating acoustic disturbance and prey variability into the PCOD model.

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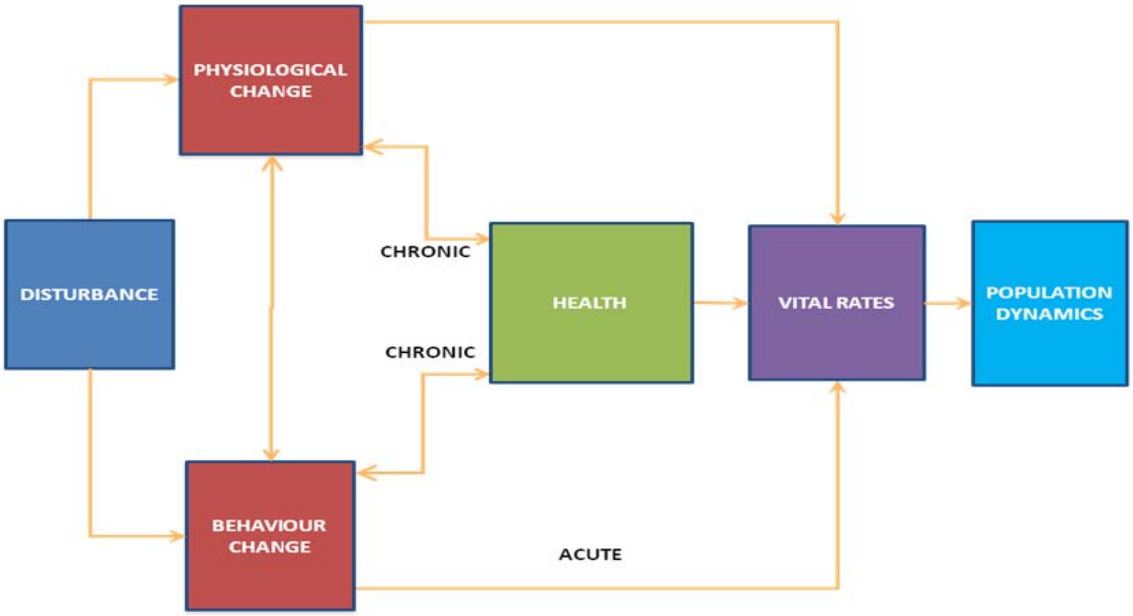

Figure 1. Modified model of population consequences of disturbance (PCOD) (Thomas et al. 2011).

OBJECTIVES

The objectives for this study are to: 1) develop a Hierarchical Bayesian Model to assess right whale biology, 2) assess the effects of health indicators on reproduction and mortality in right whales, and 3) assess the effects of fishing gear entanglements and sub-lethal shipstrikes on reproduction and mortality in right whales. The immediate objective for FY 2013 was to complete development of the appropriate model, and to start incorporating the data from entanglements and ship strikes.

APPROACH

We have continued to use and make refinements to the PCOD model developed for right whales (Schick et al. 2013). The observation model links photographic evidence of health condition to the first process model; this process model provides inference on how health changes over time. Every photographed sighting of the whales contains location information. In the second process model, we assimilate the location information together with informed priors on movement to estimate location and transition probabilities between locations. Finally, estimates of the current states (health and location) inform individual survival.

We have met regularly to review statistical output from multiple runs of the model. Typically this output has been in the form of 1) the posteriors quantifying the links between the ordinal health classes, and 2) the posterior estimates of health for individual animals. Following discussion, we have reviewed which model changes to implement. We have reconvened on a monthly basis – either in person in Boston, or over skype – to review new output, and repeat this iterative process.

In May of this year we undertook an extensive effort to deepen our understanding of the relative position of whales on the health scale, as well as the intra-individual changes in health. This involved paring the model data set back to a smaller number of whales (n = 50) over a shorter timeframe (1995-2005). The smaller data set facilitated rapid evaluation of different model formulations. Finally, in

preparation for the next two manuscripts (health, and effects of entanglement), we have begun to examine health trajectories over time in different population sub-categories.

WORK COMPLETED

We have completed the following tasks:

1. **Manuscripts** – We have published the following manuscripts pertaining to the PCAD Modeling:
    a. Schick, R. S., Rolland, R., Kraus, S., Pettis, H., Knowlton, A., Hamilton, P., Kenney, R., and J. Clark. 2013. Using Hierarchical Bayes to understand movement, health, and survival in critically endangered marine mammals. PLoS ONE 8(6): e64166. doi:10.1371/journal.pone.0064166.
    b. Schick, R. S., Rolland, R., Kraus, S., Pettis, H., Knowlton, A., Hamilton, P., Thomas, L., Harwood, J., and J. Clark. 2014. Effects of Model Formulation on Estimates of Health in Individual Right Whales (*Eubalaena glacialis*). Effects of Noise on Aquatic Life II. Springer Press
    c. Fleishman, E., Burgman, M., Runge, M., Schick, R. S., and S. Kraus. 2014. Expert elicitation of population level effects of disturbance. Effects of Noise on Aquatic Life II. Springer Press
2. **Travel** – Schick travelled to Boston meetings with the New England Aquarium researchers in:
    a. November 2012
    b. January 2013
    c. May 2013
    d. June 2013 (Schick also traveled to Duke University to meet with Jim Clark and discuss and implement a new way of imputing missing data in the model.)
3. **Workshop**
    a. We hosted an international group of right whale researchers for a two-day meeting in Boston (January 2013) to discuss ways of including both prey and acoustics into the PCOD model
4. **Model Refinement** – During our regular meetings at NEAq, we:
    a. Reviewed modeling progress by examining detailed health time series of individual animals
    b. Included entanglement data in the model
    c. Included propellor scarring data in the model
    d. Conducted a full prior sensitivity analysis on the following model components:
        R. Process variance
        S. Health proposals (starting values and monthly proposals)
        T. Movement

e. Conducted extensive analyses on the imputation of missing data for body condition and skin condition
f. Conducted an extensive analysis into the different population sub-categories
g. Began an exploration of the effect of geography on survival, i.e., we an analysis of the effects of using regional intercepts for survival in the different geographic regions

5. **Presentations**
    a. Schick et al., November 2012, Right Whale Consortium, New Bedford, MA (*Talk*)
    b. Schick et al., April 2013, European Cetacean Society, Setubal, Portugal (*Poster*)
    c. Schick et al., April 2013, Ecological and Environmental Statistical Modelling Symposium, Lisboa, Portugal (*Invited Talk*)
    d. Schick, June 2013, NCEAS Roundtable, Santa Barbara, CA (*Invited Talk*)
    e. Schick et al., August 2013, The Affects of Noise on Aquatic Life Conference, Budapest, Hungary (*Poster*)

RESULTS

One of the primary model outputs is the monthly estimates of health for individual right whales. In our model review discussions, whale researchers observed that the animals appeared to recover faster than would be expected biologically. We therefore investigated month-to-month changes in health by testing three main components of the model: 1) the maximum amount that health process variance can be each month; 2) the effect of starting point on the health; and 3) the effect of different formulations for missing data imputation. To assess the effect of these changes, we fitted the model to a pared down set of 50 animals, and only examined their health over a 10-year period. This facilitated rapid iteration over different formulations.

We found that model estimates of health were sensitive to assumptions about health process variance (Figure 1). Specifically, we found that lower values of the health variance (e.g. variance = 4) resulted in both lower apparent recovery between known observations as well as fewer small-scale changes in health at fine temporal scales (Figure 1). What that means is that the trend in estimated health is smoother and less responsive to observed changes in health. In contrast, as the process variance values get larger (e.g. variance = 16), we see more apparent recovery from periods of lower health (Figure 1).

We next compared the effect of starting health values on final health estimates. That is, we ran the Gibbs sampler with several MCMC chains with different starting values. We did not see any effect of starting position (results not shown), as the prior connecting the ordinal classes of health with continuous health swamped this effect (results not shown).

Lastly, we examined the effect of missing data imputation on the results. The first iteration of the model (Schick et al. 2013) had a sub-process for imputing health for missing body condition observations. This routine was set to probabilistically impute observations based on long-term conditions of the animal, i.e., if the whale was most often seen in body condition ‘thin’ then the multinomial sampling probabilities for the missing data point reflected this. As a first attempt, this seemed reasonable, but it had the unwanted side effect of causing an apparent recovery for animals during periods of missing data.

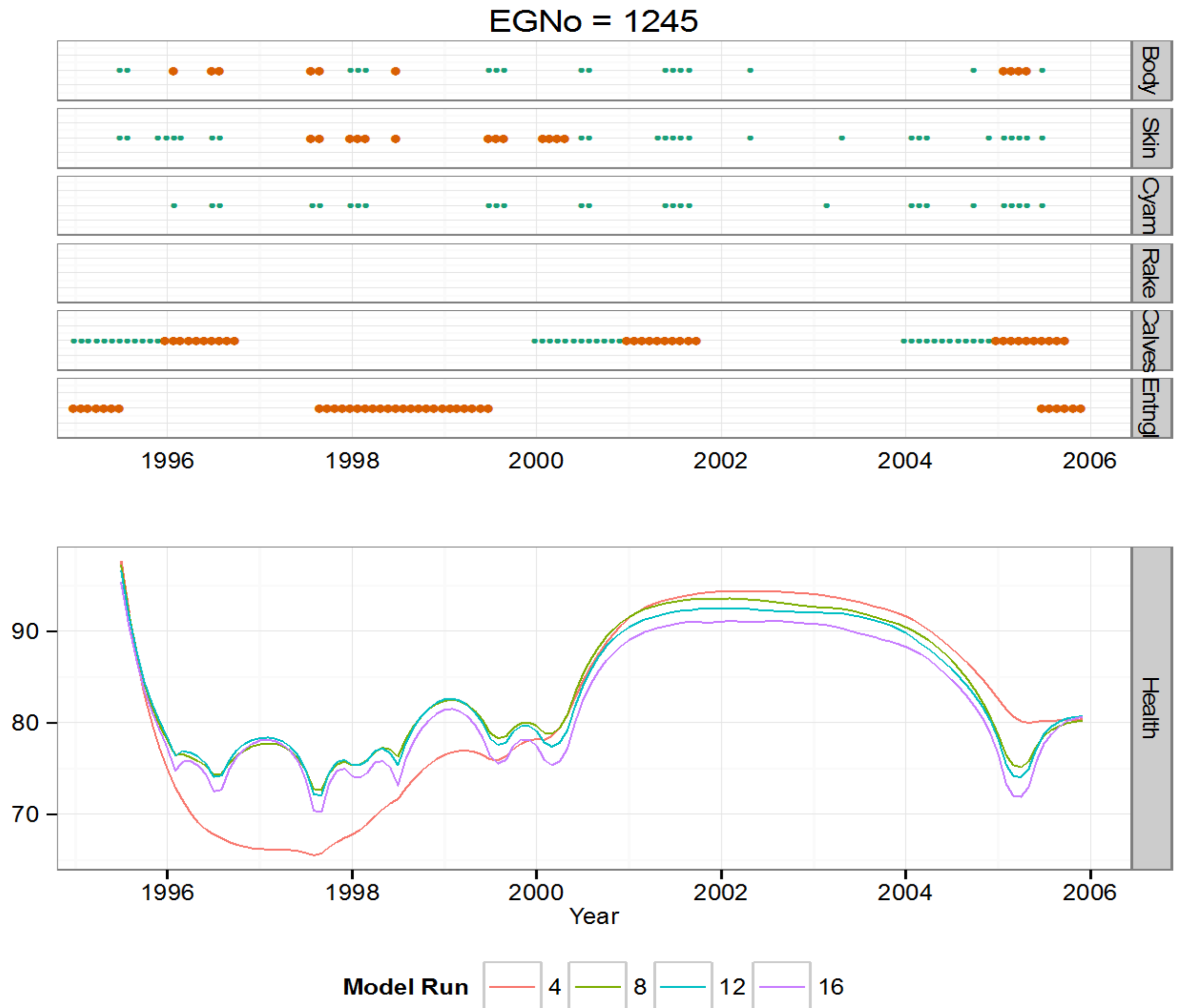

Figure 1. Monthly estimates of health for EGNo #1245. Upper panel depicts observed health and reproductive status for 1995-2005. Lower panel depict health estimates for these same years using 4 different process variance values (4, 8, 12, 16). At the smallest levels (4) the health trajectory is very smooth and less responsive to the data. In contrast, at higher levels (16) there is more apparent recovery between known observations, e.g. 1997.

We experimented with a new data imputation scheme that assumed the prior for an animals' missing health state will be based on a linear interpolation between known observations. We also tested the effect of not imputing missing data. We found that assumptions about missing data had a strong effect on health estimates. Note how much less health recovers during periods of missing data, e.g. 1999 (Figure 2). Health estimates are also much less certain when no missing data are imputed (Figure 2, bottom), so after review, we settled on the linear interpolation procedure.

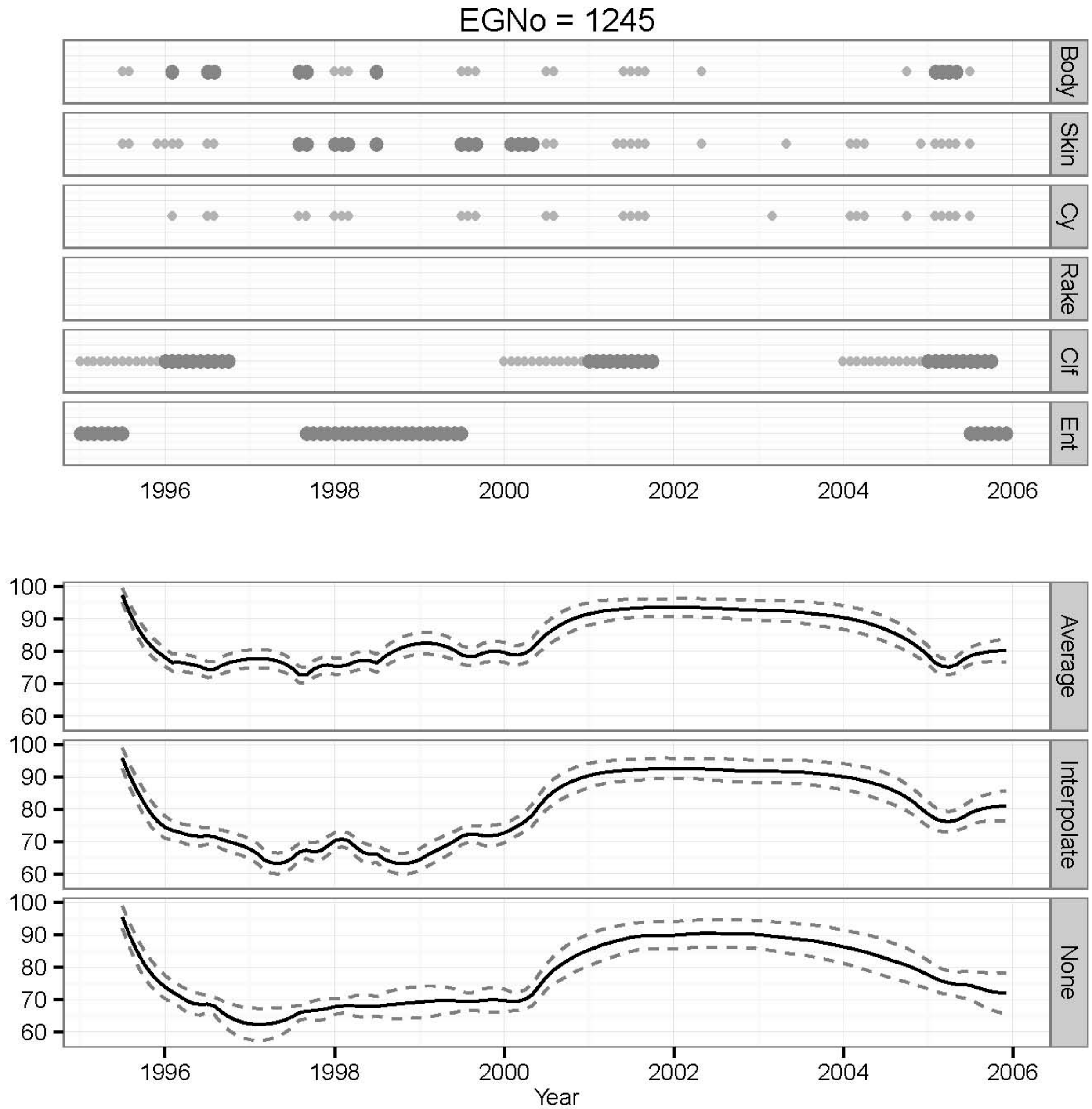

Figure 2. Effects of missing data imputation on estimates of health for EGNo 1245. Upper panel depicts observed data for 1995-2005. Lower three panels highlight health estimates using three different assumptions about missing data imputation: 1) "Average," i.e. the prior probabilities for the multinomial are informed by the long term average body condition values; 2) "Interpolate," i.e. the probabilities for the missing data are informed by the two nearest (in time) observations; and 3) no imputation.

We then examined the impact of using informed priors for the monthly movement transitions. Results indicated that the model was sensitive to these assumptions, particularly in the less well-studied areas, e.g. the Mid-Atlantic region (Figure 3).

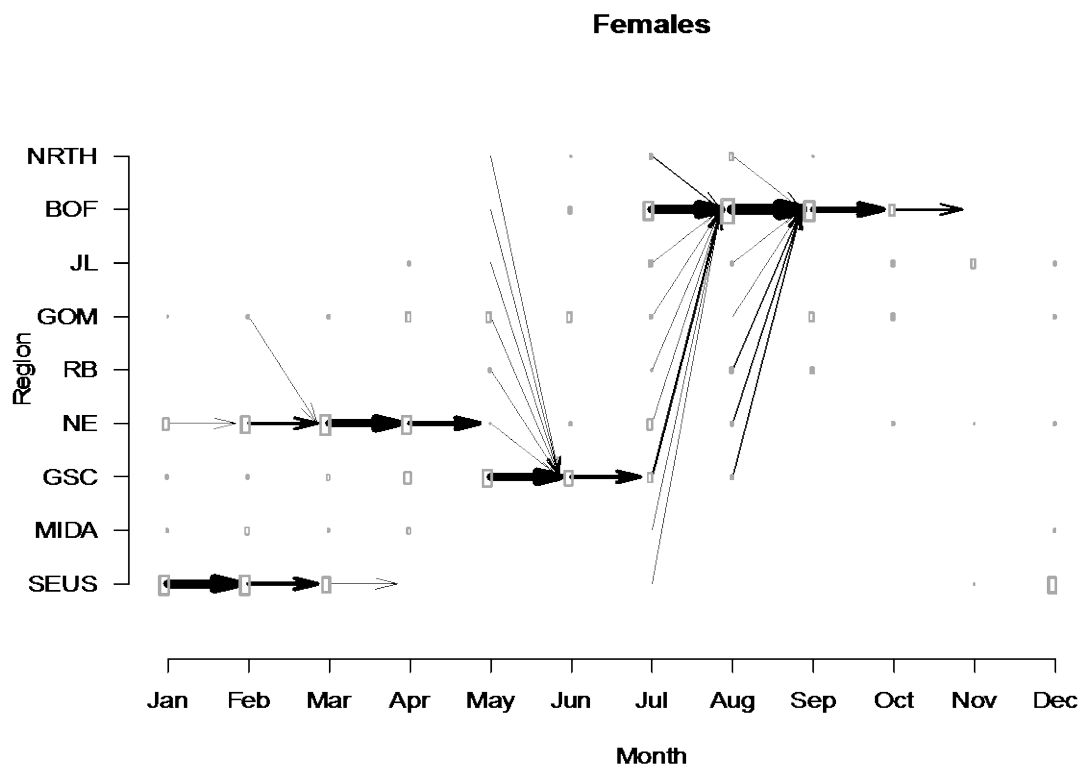

Figure 3. Summary of movement transition probabilities for adult female right whales. Arrows depict transition probabilities above 0.25; thickness of the arrows corresponds to the magnitude of the probability. Here we used flat priors and as a result no probabilities > 0.25 were estimated in the Mid-Atlantic.

In preparation for the next manuscripts, we have looked at the estimates of health for the entire population. However, because there are periods of naturally poorer body condition for certain sub-categories, e.g. lactating females, we have also examined health estimates for different sub-population categories.

While the results are preliminary, we do see large variability and some dramatic decreases in population level health (Figure 4). We can also observe the contrast between males and females. Whereas males appear to have recovered from a period of poor health in the late 1990's, several different categories of females have variable and declining health over time (Figure 4).

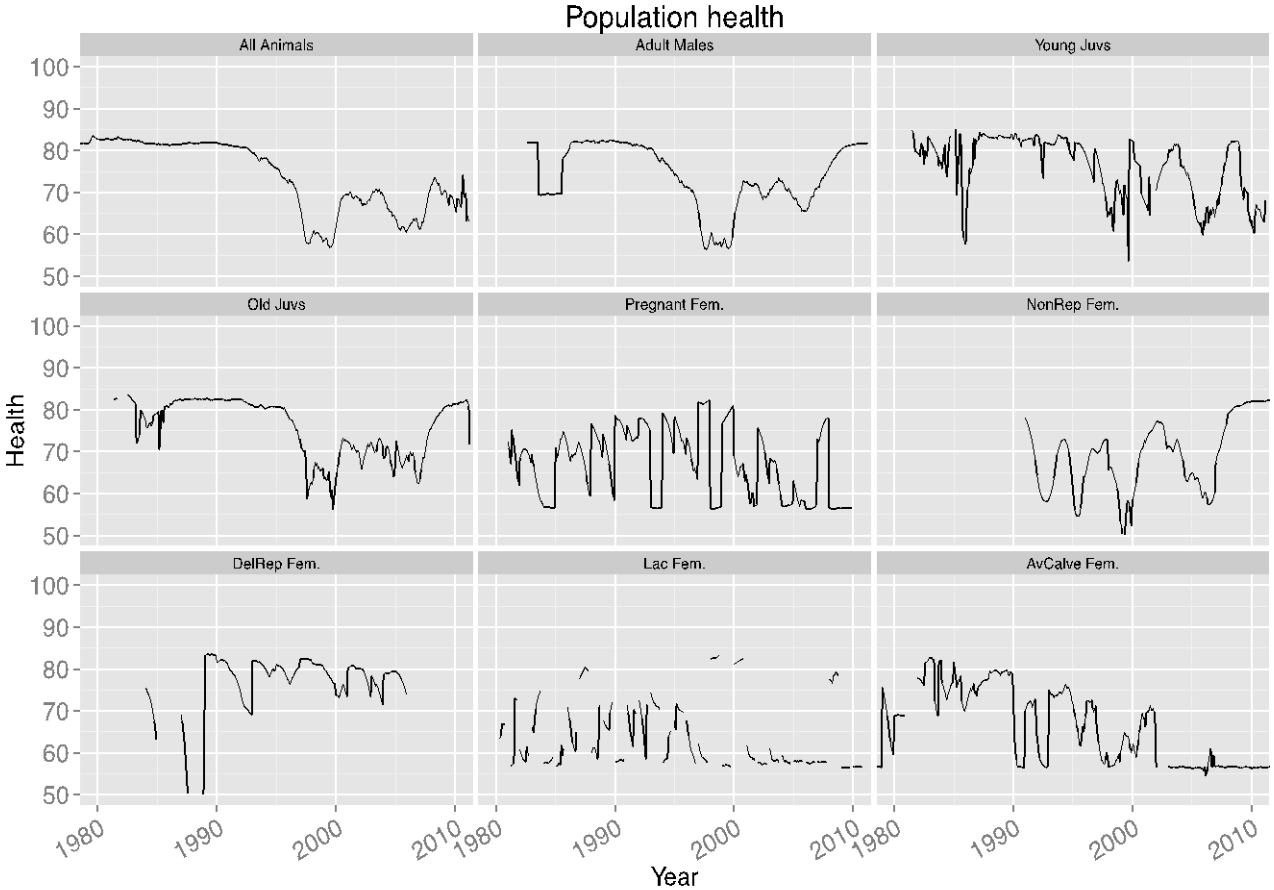

Figure 4. Health estimates for the entire right whale population (top left) and 8 sub-population categories. Note the apparent decline and recovery of Adult males and Old juveniles (3-9 years old). In contrast, the health of females is much more variable. In particular, note the declining health of those females who were available to calve in a given year, but who have not calved (AvCalve Fem.).

Finally, the January workshop on the potential expansion of the PCOD model to prey species availability and acoustic disturbance did not lead to a clear path forward. Many ideas were put forward, but there was no unanimity in the discussion about potential applications. We have concluded that after the model is running well with the existing data, we will revisit the potential for incorporating already collected prey and/or acoustic data, as well as the potential for experimental work that might inform the model.

IMPACT/APPLICATIONS

Despite continuous protection, studies, and monitoring, North Atlantic right whales have been critically endangered for decades (Kraus et al. 2005). Previous population forecasts have been ominous (Caswell et al. 1999, Fujiwara & Caswell, 2001), and several dips in vital rates of the population have been documented in the past 20 years (Kraus & Rolland, 2007). These analyses may be able to provide a comprehensive and quantitative understanding of the many factors that impact the health of North Atlantic right whales. This approach can help identify those anthropogenic or natural stressors which

most affect mortality and/or reproduction, and will fill a critical need as different management scenarios and/or interventions are considered.

We are using these data in the preparation of the next two planned manuscripts. For the first manuscript, aggregated individual health estimates will be used together with the sub-population health summaries from Figure 4 to more completely understand past population trajectories, but also to understand how future changes in health may reflect particular disturbances.The second manuscript will use the individual health estimates together with information on the start/stop times of entanglement events and their severity to examine how health changes during these times. In addition, we will use estimates from the movement component of the model to provide information on where the animals are most likely to become entangled.

While these model analyses are focussed on right whales, photographic observations of condition have been used to evaluate health in other cetaceans (see, for example, Bradford et al. 2012). Therefore, it is feasible to extend this model to other well studied species. By using photographic observations with this modeling approach, we can evaluate how the condition of whales varies over time and space and in response to specific extrinsic factors. This will increase our knowledge of the foraging ecology of marine mammals, and provide critical insight into risk factors for both individual whales and their populations.

RELATED PROJECTS

The New England Aquarium's Ocean Health and Marine Stress Program includes studies of stress in beaked and sperm whales (R. Rolland, PI; ONR # N000141110540), and a study on the detection and use of hormones from right whale respiratory exudate (K. Hunt, PI; ONR # N000141310639). As part of the New England Aquarium's Marine Health Program, we are involved in the broader PCOD modeling studies (Len Thomas, PI; ONR Contract # N000141210286) .

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